Context scenarios

and their usage for the construction of socio-technical energy scenarios

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Abstract

Model-based energy scenarios are a widely used tool for supporting economic and political decision makers. The results of energy modeling and the conclusions deduced therefrom, however, depend on the model input data derived from framework assumptions about future developments in the embedding society, which are deeply uncertain in the long term. The challenge to deal with this 'context uncertainty' in a systematic and comprehensive manner has only recently started to attract intensified attention in energy research; the search for appropriate methods is ongoing. This paper proposes a new concept for the construction of socio-technical energy scenarios, which combines familiar environmental modeling approaches with new developments in qualitative scenario methodology, and demonstrates the possible application of the concept in model-based energy scenario construction.

Key words: *energy scenario, energy modeling, cross-impact balance analysis, socio-technical scenario, context scenarios*

1. Introduction

These days, model-based energy scenarios are a well-established practical tool informing public debates, corporate decision makers and policy advisors about possible futures, options, and policy effects [1]. Traditional energy scenarios achieve this by focusing on the technical and energy-economic dimensions of the future describing the deployment of techniques, changes in energy demand and supply, in emissions, in supply costs and the like. Determinants of the energy future located outside the immediate energy system, such as demographic and economic developments, innovation dynamics, changes in public attitudes, social values and consumer behavior are, despite their deep uncertainty in the long term, mostly treated as fixed framework assumptions. On the other hand, the pronounced influence of the framework assumption on model results is well known to energy modelers [2]. This begs the question how much reliability can be expected from results and the conclusions derived therefrom, bearing in mind that they critically depend on deeply uncertain assumptions – if these uncertainties are not adequately dealt with.

Adequately dealing with the 'context uncertainty' in energy modeling, however, is not an easy task. It requires an uncertainty assessment for each relevant framework assumption, while taking into account the interdependences between the various context developments. All this needs to be done in a broad field of research questions, which transcends disciplinary boundaries, at the same time also including qualitative forms of knowledge. Basically this means beginning the exercise of constructing *energy* scenarios with an effort, aimed at providing a better understanding of the range of possible futures of the *society* into which the energy system is embedded. Furthermore, to do justice to the scientific character of the subsequent energy systems analysis, this preparatory step should be systematic and meet minimum standards of transparency, traceability, and intersubjectivity (if objectivity cannot be achieved) – criteria that are not easily fulfilled in the construction of qualitative societal scenarios.

This article describes an approach to better address the uncertainty of societal framework assumptions in energy modeling and the socio-technical character of energy transitions. The 'context scenario' approach was developed in the years 2011-2014 as part of the research alliance ENERGY-TRANS, a platform for interdisciplinary research activities dealing with the socio-technical aspects of the German energy transition ('Energiewende') [3].

Scenarios, including energy scenarios, can assume different roles in foresight exercises and this diversity has its impacts on the role and usefulness of the proposed context scenario approach. Börjeson et al. differentiate between 'predictive' (e.g. what-if), 'explorative' and 'normative' scenarios [4]. The most pronounced effect of the proposed approach can be expected in the case of explorative energy scenarios which deal with the question '*what may happen?'* because, obviously, a comprehensive answer to this question must exceed the closer energy system and put the same question also to the major drivers of the energy system. Hence, this case is the focus of this article. This does not mean, however, that the context scenario approach is not relevant for other types of energy scenarios: In '*what-if* scenarios' (*if-then* scenarios) the 'if' condition usually is restricted to a small part of the model's input data set (for instance, a specific economic development or a specific political action), excluding the wide range of all other drivers. This means that the *if-then* answer constructed by the model may well critically depend on the assumptions about the excluded drivers, a fact challenging the robustness of the *if-then* analysis, when done in a traditional model-only style. Normative (*'what should happen'*) scenarios, on the other hand, are bound to a desired final state and not open to variations in this respect. Nevertheless, they may be open to the question which pathways to the final state might be advisable or simply feasible under different framework conditions. Hence, the context scenario approach should be, to varying degree, relevant for all types of energy scenarios.

The relevance of the context scenario approach depends also on the type of energy model employed in the scenario exercise. In energy systems analysis a bunch of different types of models exist. The most common are techno-economic models, like TIME PanEU [5]. Furthermore, economic models, like computable or applied equilibrium models (e.g. GTAP-E, see [6]), agent-based models and systems dynamics could be named. Generally spoken, the proposed approach should be useful for all model types in which the model is driven by a non-trivial set of uncertain and interrelated exogenous assumptions. This is typical for techno-economic and economic energy models. To which extent this applies also to agent-based models and system-dynamic energy models depends on the set-up of the model exercise.

The following chapters describe the motifs and the inspiration the authors took from climate change research and other research fields. The concept of context scenarios is outlined and its usage for the construction of socio-technical energy scenarios is shown using a demonstration exercise. Finally, strengths and limitations of the concept are discussed.

2. Motivation

To generate future energy system pathways, a great number of assumptions have to be defined, which are ex- and implicitly taken into account in the model, e.g. concerning demographic development, gross domestic product (GDP) growth, increases of energy efficiencies and many others (see e.g. [2] and appendix Table A.1). All of these assumptions are associated with considerable uncertainty when it comes to long-term scenarios, and they imply an assessment and interpretation of current knowledge. This interpretation – which is always a part of the scenario generation process and usually not fully transparent – leads to a selection of exogenous techno-economic, political, and societal factors, together building a certain story about the future of the embedding society on the one hand and to the neglect of other possible assumptions and underlying stories on the other hand. One example are the assumptions on population growth included in International Energy Agency (IEA) studies: the IEA energy scenarios [7] are based on data published by United Nations Population Division (UNPD) [8]. UNPD analyzed different scenarios on population growth based on different societal development pathways. However, IEA – following a very common procedure - only used the data for the medium case, ignoring that this case reflects only one possible option. As a result, the scenarios published by the IEA might only reflect a very restricted spectrum of possible developments. Other examples often cited are GDP development and the derived assumptions about energy demand, and sensitive assumptions relating to fossil fuel prices, technology costs and CO_2 emission costs. This focus on *one* set of assumptions and *one* underlying story as a starting point for the model analysis may cause an unwise **limitation of the bandwidth/variety of derived energy scenarios** that is considered as possible even if sensitivity analysis is applied to test the influence of some of the assumptions.

Furthermore, a sound choice of assumptions in different fields (demography, economy, technological progress and others) requires careful consideration of the complex interdependencies between developments in all these fields, or as IEA put it "Key drivers of energy markets are hard to predict, in part because they interact with each other" [9]. This cross-disciplinary effort frequently lacks documentation in the scenario studies (if done at all) and a **lack of internal consistency** cannot be ruled out in such cases.

Internal consistency among (mathematically related) numerical assumptions can be managed more easily using quantitative approaches than qualitative approaches. However, quantitative approaches – usually used for energy scenarios – have the disadvantage that those factors that cannot be expressed in numbers are either more or less ignored, or set implicitly as constant. This may limit the suitability of existing scenarios and scenario studies for a broader range of research questions (see e.g. [10]). All of the exogenous factors employed as drivers in the model analysis, not to mention any endogenous factors (often calculated by cost optimizing objective functions) are based on various societal assumptions such as behavior patterns, attitude to technical changes, or public acceptance. Usually these are either only included implicitly, or are simply ignored in energy scenarios (cf. appendix Table A1). The results are **conclusions that risk being of limited robustness** and consistency.

One striking example of how far energy models can mislead when the stability of the societal and political environment is overrated, was highlighted by Mai et al. They described the repeated and pronounced underestimation of U.S. wind turbine deployment by energy models in the period 2001-2009, explained partly by static policy assumptions in a dynamic socio-political context [11].

Compared to common practice, a methodology that combines a quantitative approach, where possible, with a more explicit appraisal and a deeper analysis of societal assumptions should result in a far better understanding of transition processes, as well as the risks and robustness concerning possible developments in the societal context. The benefit of doing so can be observed in several other research fields.

3. Learning from other fields

The challenge of adequately defining scenario assumptions that represent the uncertainty and complexity of future *social* development is not merely confined to *energy* scenario analysis. Instead it involves any fields that require such assumptions on societal futures as input for technical and/or environmental modeling - environmental change research, for example. Energy scenario analysis can therefore learn from the methodological answers to this challenge developed in related fields.

In this section based on literature review, the so-called 'Story and Simulation (SAS)' [12] approach from the field of environmental scenario analysis is therefore briefly described, followed by a short discussion of its benefits and limits, including the latest developments from the field of climate change research.

3.1 "Story and simulation (SAS)" - a methodology for environmental scenario analysis

In the field of environmental scenario analysis, an approach has been developed in the last 15 years which proposes combining storylines, i.e. qualitative, textual or even narrative descriptions of societal (political, institutional, etc.) futures with numerical simulation models. The approach is based on the much older idea of combining quantitative or 'hard' systems thinking (cf. e.g. [13]) with qualitative or 'soft' systems thinking [14]. It has been established mainly under the label of "Story and Simulation (SAS)" by Joseph Alcamo [12], but is also called "integrated scenarios" (e.g. [15]), and "narratives and numbers" (e.g. [16]), or "hybrid scenarios" (e.g. [17]).

The basic idea of SAS is first to construct a broad set of qualitative storylines, to translate the driving forces of the storylines into quantitative sets of input parameters for the numerical model, and to use these sets for scenario simulation. The storylines are often constructed together with experts in form of workshops. The SAS methodology results in 'hybrid' scenarios, comprising qualitative context descriptions and quantitative model calculations of system consequences. The approach relies on the principles of *consistency control* and *iteration*: the authors suggest that modeling and simulation are used "to identify inconsistencies in the storylines" ([10] and others), and thus recommend revising the storylines after simulation. Iteration may then become necessary, adapting the input-parameter sets to the refined storylines and repeating the simulation.

SAS has become state of the art in scenarios of environmental change [18]. It has been applied to multiple fields, such as water management (e.g. [19]), biodiversity (e.g. [20]), sustainability (e.g. [21]), land use (e.g. [22]), and its perhaps best known application in the field of climate change research, documented in the International Panel of Climate Change's Special Report on Emissions Scenarios by (IPCC SRES [23]). However, integrated qualitative-quantitative scenario methodologies have also been developed and used in other fields such as industrial ecology (see e.g. [24]) and economics (see e.g. [25]).

3.2 Critical discussion of SAS and latest developments in the field of climate change research

Though it has plenty of appeal, the SAS approach is also fraught with difficulties. Its central benefits, compared to the current practice of energy scenario analysis are ([26], see also [27]):

a) *Qualitative factors* are not ignored and excluded, but are considered and *included* through the storylines.

b) *Assumptions* on future (social) developments behind indicators and time-series used as model input do not remain hidden but are made *explicit*.

c) Instead of assuming only one possible social future (e.g. with regard to population growth), the *uncertainty* of social developments is addressed through a bandwidth of storylines covering different future alternatives – and this not only for *single* developments but in the form of comprehensive pictures.

The key limits and challenges of SAS, also recognized by the SAS authors themselves (e.g. [10]) are:

a) Qualitative storylines suffer from a lack of *reproducibility* originating from a lack of *transparency,* as they are based on “assumptions and mental models of storyline writers [that] remain unstated” [10].

b) The *conversion, i*.e. the translation of qualitative into quantitative knowledge remains “one of the weakest links in SAS procedure” [10], and finally it is always reliant on expert judgment, even in the application of formalized translation/conversion techniques [10], for instance, proposes using fuzzy logics; Kemp-Benedict proposes using Bayesian statistical reasoning [28].

In the field of climate change, there is ongoing critical discussion of the SAS approach; ways to take it forward are being developed. For instance, Garb et al. commented: “Indeed, there is a growing imbalance between the increasing technical sophistication of the modeling elements of scenarios and the continued simplicity of our understanding of the social origins, linkages, and implications of the narratives to which they are coupled” [29]. Regarding this weakness of the storyline part, the recommendation has been formulated (e.g. [18]) to use more *systematic and formalized* approaches to construct storylines, i.e. approaches that go beyond the mainly used ‘intuitive logics’ (IL) technique [30]. Cross-impact balance analysis (CIB, [31]), a qualitative form of systems analysis, is currently being discussed as a potential alternative for developing the qualitative part of the combination (e.g. [32]). Schweizer and Kriegler for example have demonstrated empirically with the help of CIB that the internal consistency of the storylines was *not* assured for all storylines of the IPCC SRES [33]. Thus, the principle of consistency control has not been successful in this case. Furthermore, the SRES scenario sample lacked other possible and internally consistent storylines. Moreover, the advantages of CIB compared to IL in terms of objectivity have also been discussed from a philosophy of science perspective [34]. A proposal to use CIB in constructing global socio-economic pathways for climate change research has been made [35] within the new IPCC framework of shared socioeconomic pathways (SSP) [36].

3.3 State of transfer to energy research

Considering the methodologies developed in other fields and the benefits achieved thereby, it is not surprising that several energy modelers got interested in the transfer of the SAS concept to energy scenario construction. Indeed, an increasing number of energy researchers apply storyline + model approaches, some aiming at incorporating stakeholder views into the model exercise, some using storylines as a means of expressing input uncertainty. The Tyndall Decarbonisation Project developed a series of storylines about desirable decarbonisation end points before quantitatively backcasting the respective pathways ([37], model results are described in [38]). Stocker et al. reutilized storylines developed by a previous biodiversity project [39] to develop coherent sets of policy measures informing an econometric model (GINFORS) [40]. Economic data as well as energy and emission developments were calculated for the EU 25 for each storyline. The CLUES project designed four storylines about the UK energy system 2050 and subsequently quantified the storylines using the Tyndall model [41]. Gouveia et al. developed projections of energy services demand for residential buildings for Portugal and checked the robustness of their TIMES-PT model results using 'sensitivity analysis scenarios'; no detailed information about their construction is available [42]. Capellán-Pérez et al. used a meta-study about global socio-economic scenarios [43] to define a set of storylines, driving a system-dynamics energy model with focus on global fossil fuel depletion [44]. Following a long-lasting tradition, Shell's global energy scenarios were based on two alternative narratives describing global trends in various fields [45]. O'Mahony proposed a combined IL-storyline and energy simulation approach for short-term energy scenarios [46]. The concept was applied in a project analyzing energy futures for Ireland [47]. Trutnevyte et al. used one (exemplary) storyline to inform eight energy models ('landscape of models') simulating the UK power system transition. The exercise delivered particular insights into the difficulties of storyline translation and the benefits of storyline-model-iterations [48]. McDowall described a 'dialog' between narrative socio-technical scenarios and energy system modeling in the field of hydrogen energy [49]. Narrative scenarios expressing stakeholder views were constructed in an IL-style. They were used to take benefit of a 'constructive conflict' between storylines and model exercises. Fortes et al. developed long-term energy scenarios for Portugal [50]. Stakeholder workshops prefaced the TIMES-PT model exercise. They designed two narrative scenarios each 'providing a coherent context for modeling assumptions'.

Though this overview clearly reflects a trend towards increasing storyline application in energy research in recent years, storylines usually are constructed in a rather classical, i.e. nonformalized, frequently discussion-based style comparable to the IL approach used in climate research. The critical discussion in climate research about more systematic, traceable and by this, more 'scientific' storyline construction methods (cf. section 3.2) was hardly noticed in energy research, so far. Rare exceptions are Hansen et al., applying CIB scenarios to link sectorial energy modeling with national and global developments [51], and Ruth et al., using CIB based 'framing scenarios' (developed by Wachsmuth et al. [52]) as a starting point for a climate-driven regional agriculture-energy model analysis [53]. Against this background, it is the purpose of this article to pave the further way for an intensified use of systematically derived 'hybrid scenarios' in energy research. It presents a coherent concept how to develop 'context scenarios' in a systematic and traceable way. Using a demonstrator comparing a model-only and a context-scenario-plus-model-analysis the article illustrates the difference the concept can make and how this can lead to an advanced understanding of the role of context uncertainties in energy modeling.

4. The concept of context scenarios and the construction of socio-technical energy scenarios: an overview

As outlined in Chapter 3, the SAS approach has been applied in environmental modeling for decades, with the aim of reflecting the uncertainty of dynamic and complex systems more accurately. Discussions about energy modeling, which deal with an equally complex and dynamic (socio-technical) system, have only recently started to address the need to achieve a better reflection of socio-technical ’complexity’ in energy scenarios (cf. chapter 3.3).

To improve the operationalization of SAS in energy research, the proposed concept uses a more systematic method of storyline construction - CIB analysis - as argued in Chapter 3. The basic idea is to substitute ‘intuitive logics’, the SAS story construction method, with the more formalized CIB method. The Cross-impact balance method “can be understood as a heuristic procedure that supports the analysis of qualitative knowledge about the interdependence of system elements” [54]. When approaching complex systems such as socio-technical systems, “soft” knowledge [46], which is qualitative in origin, is equally important as “hard” and quantifiable knowledge. Realizing scenario exercises with CIB enables such heterogeneous types of knowledge to be included as input data.

CIB can be understood as an improvement of a traditional scenario method named ‘field anomaly relaxation´ [55] or ‘consistency matrix’ [56]. Enriching this method with motifs from cross-impact analysis (CIA, [57]) results in a method capable of evaluating qualitative impact networks in a simple and transparent way. As a general purpose qualitative systems analysis tool, CIB has been applied in various research fields, including biotechnology [58], waste (e.g. [59]), energy (e.g. [60]), environmental modeling [61], health (e.g. [62]), climate change (e.g. [33]), innovation [63], sustainability (e.g. [64]) and others. A bibliography of CIB applications can be found at [65]. The workflow for constructing CIB-based context scenarios, exploiting them to inform energy model analysis, and for combining both parts of the analysis to produce hybrid ‘socio-technical energy scenarios’ can be sketched using the following steps:

I. **Context analysis**
   a. **Defining the context.** In a first step the most important factors, so called ‘descriptors’ [66], with significant direct or indirect influence on the energy systems analysis, need to be identified and collocated using desk research, expert workshops, or other participatory approaches. If influences from the energy system are expected to feed back into the context, the respective energy variables generating the feedback also need to be added to the list of descriptors. The list of descriptors (typically 10-20 descriptors) then builds the elements of the system under study.
   b. **Identifying the future uncertainties of the context.** Next a small set of alternative futures (typically 2-4) is defined for each descriptor, roughly representing the possible and deemed probable developments of the descriptor, which are then included in further analysis. The different types of knowledge (relating to qualitative and quantitative descriptors) are integrated in the analysis in the form of short essays describing the state/content and the

possible/plausible future developments of each descriptor, and may have either a numerical or linguistic characterization.

c. **Analyzing the interdependences.** The next step of CIB analysis is the qualitative yet systematic judgment of direct cross-impacts between descriptor futures (using an integer scale from -3 to +3 and verbal explanations, see Chapter 5). The preparation of the 'cross-impact matrix' is a genuinely interdisciplinary task and must be realized within a multi-discipline work setting, using participatory approaches to gather expert judgments, either individually, in group exercises, or by desk research.
d. **Constructing the context scenarios.** The core of the method is a balance algorithm, which scans all possible combinations of descriptor futures (typically 10^4-10^7 combinations), checks the internal consistency of each of them by balancing all promoting and hindering impacts between the descriptor futures, and identifying a set of 'consistent scenarios', each comprising a set of mutually supporting descriptor developments (typically 5-50 scenarios). In each case, the result is a network of interacting developments reflecting the overall (socio-technical) system relations between the chosen elements. The output is a set of raw scenarios, which still needs refinement, interpretation of the inner scenario logic, and verbally formulated stories [67].

II. **Energy model analysis**

a. Each context scenario, describing a distinct, yet internally consistent future of the social, political, technological and economic context conditions of the energy system, is 'translated' into a specific set of model input parameters by a joint exercise of context scenario constructors and energy model experts.
b. The energy model generates model outputs for each input parameter set, depicting the 'energetic fingerprint' of each context scenario. The differences between the outputs of each model run reflect the diversity of energy system responses to the range of possible context futures.

III. **Building and exploiting hybrid socio-technical energy scenarios**

a. Merging each of the (qualitative) context scenarios with its associated (quantitative) model output results in a consistent description of one possible future of the combined system 'context system + energy system' (hybrid scenarios) explaining the interplay between both system parts (as far as addressed by the selected descriptors of the context scenarios).
b. The derived set of socio-technical energy scenarios can be used to study the uncertainties of conclusions derived from the scenario study, to identify socio-technical opportunities, challenges and preconditions for envisioned energy goals, and to develop strategies that make a desired energy pathway more resilient to an uncertain future of the embedding social context.

5. Concept demonstration

5.1 General remarks

To exemplify the approach of 'hybrid' (socio-technical) scenarios, while showcasing their advantage over the traditional approach of energy system scenarios that exclude societal embedding, a simplified demonstrator example is discussed in the following paragraphs. For simplicity, the demonstrator is only based on a relatively low number of societal descriptors. Inevitably this entails the exclusion of some highly relevant issues from the demonstrator analysis, for instance the issue of energy supply security, which is addressed only in a very rough and indirect manner in the demonstrator.

Moreover, the selected thematic and regional focus of the demonstrator (energy transition in Germany) leads to a specific focus for the topics of the context scenarios. Again this should be understood as an example. Selecting a different thematic and/or regional focus for the demonstrator, which would have been possible also, would have shifted the relevant technology mix (e.g. including nuclear power), energy application fields (e.g. including water desalination for fresh water supply in dry regions) and resource scarcities (e.g. including trained human resources): In each practical application of the context scenario approach the thematic and regional focus requires a very specific selection of the descriptor set.

Furthermore, the assessment of the cross-impacts has been done by the authors, whereas in research projects, this is usually done by extensive interviews, or workshops with experts from the fields relating to the different descriptors. The energy system model used for the demonstrator is a significantly stripped-down version of DLR's scenario model [68]. The quantitative coupling between social and selected technical scenario components does not provide a detailed analysis of possible non-linear relationships between social-economic indicators and energy-related quantities. The demonstrator can therefore *only* be meant to highlight the basic concepts of coupling social and technical scenarios in an integrated approach. Having said this, the demonstrator approach is robust insofar as it is capable of showing the shortcomings of the traditional energy scenario approach (i.e. which either ignores or inconsistently considers social context), and illustrating the benefits of the integrated socio-technical approach for energy scenario construction. An advanced study presenting the coupling of full-scale context scenarios with detailed energy system scenarios, however, is under preparation.

5.2 The assumed (fictitious) task

In general, energy scenarios are used to describe possible future energy system developments and to analyze the economic and ecological consequences of different development paths, the complex interplay between different energy system components, the feasibility as well as critical preconditions for and barriers to the intended energy system transition. In the end, the aim is to provide information and to derive guidance for decision makers in politics and industry, and the public. To demonstrate critical differences between the traditional and the coupled socio-technical scenario approach, the fictitious task of deriving policy advice on the question: "Are the goals of the German 'Energiewende' feasible?" is assumed. An analysis is conducted for both approaches ('model only' and 'context scenarios + model'). As this is only a demonstration exercise, the analysis is limited in its extent and the results should be understood as merely being of illustrative significance.

5.3 The traditional approach

The analysis of the traditional approach is based on a simplified energy system model for Germany (target year 2040), which calculates final energy demand (sectors: industry, households, commerce & trade, transport), gross electricity consumption, the share of renewable energies in heat and electricity production, the consumption of biofuels in transport, as well as the resulting CO_2 emissions. Driving factors for energy consumption are the development of GDP and population, as well as energy intensity estimates (i.e. average fuel consumption per mile, power consumption per capita in households, final energy consumption per € GDP in industry etc.).

In the reference case, the development of GDP, population, and transport services are taken from Schlesinger et al. [69], which – in turn – are based on estimates of the expected (most likely) development of these quantities. The development of energy intensity is based on scenarios from Nitsch et al. [70], which assume ambitious developments, yet take technical potential and barriers into account as constraints (see also [68]). Table 1 shows some numerical results of the respective model calculations (‘reference scenario’).

Table 1: Selected results of reference scenario calculations. Goals relevant to the calculations relating to the German ‘Energiewende’ by 2040 are: -70% greenhouse gas emissions 1990-2040, 45 % share of renewables in final energy demand, 65 % share of renewables in electricity production, 0 % nuclear power in 2022 [71].

Table 1 shows that the reference scenario roughly meets the goals. The model delivers additional data about the time steps till 2040, the shares of renewable and conventional supply technologies, and consumption structures. Based on the scenario analysis conducted so far, a symbolic (fictitious) piece of policy advice might sound something like this:

> *“Yes, the 2040 goals of the German ‘Energiewende’ are – more or less – feasible, provided that ambitious measures concerning the expansion of renewables and energy efficiency are undertaken.”*

However, from the perspective of context scenarios, this conclusion is open to criticism:

The conclusion of feasibility is correct only if the assumed context conditions (population, GDP, energy prices, technology development, and more), *which are not controlled, or controlled only to a limited extent by German energy policy makers*, turn out to be valid. The analysis does not shed any light on the question whether the statement of feasibility is robust under different, yet equally plausible context conditions.

A traditional approach to dealing with the uncertainty of input assumptions is sensitivity analysis, which is generally performed by varying a single factor, while keeping all other factors constant. In the demonstrator example, the energy system model was used to test the sensitivity of both final energy consumption and energy-related CO_2 emissions on GDP development: in the reference scenario, a GDP growth of 0.9% per year is assumed, resulting in a GDP in 2040 of 2941 billion $€_{2000}$. The first sensitivity test assumes weaker GDP growth (0.5%/a, i.e. 2611 $€_{2000}$ in 2040), the second sensitivity test stronger GDP growth (1.5%/a, resulting in 3514 $€_{2000}$ in 2040). Results are shown in Figure 1.

Figure 1: Sensitivity test for GDP. Reference scenario: closed circle. Results for modified GDP assumptions: open circles. Data show model results for German final energy consumption and energy related CO_2 emissions in 2040.

Based on this analysis, a piece of an – admittedly very simple - policy advice might be:

> *"The feasibility statement made above does not critically depend on parameter uncertainty (as tested so far). If climate protection targets are to be met closely, however, economic policies should aim at low economic growth."*

This advice, however, ignores that a change in economic development is unthinkable without effects in other fields, which would have their own impact on the energy system. The advice therefore needs to be revisited with the insight derived from the following section.

5.4 The context scenario approach and the perspective of socio-technical scenarios

This approach does not aim at varying single factors to test the robustness of the model results. Instead the whole story behind the input assumptions of a model is changed for each run. Changing the story means that the change generally involves several input assumptions at once. Consistency, however, is the key challenge: the new story should not be a mere random guess - it once again has to be a plausible and understandable narrative. The first steps of storyline construction consist of choosing the storyline descriptors and their alternative futures (the 'variants', see chapter 4.1). For the purpose of the demonstrator study, a set of 13 descriptors was chosen (see Table 2), of which six are quantitatively coupled to the energy system model (population, GDP, RES growth, domestic and industrial energy savings, and mobility structures), addressing some of the model's input data. Definitions of descriptors also include, where appropriate, a numerical translation of the key words used in Table 2. Economic growth weak/medium/strong, for instance, was translated into GDP growth of 0.5 / 0.9 / 1.5 % per year, in accordance with the sensitivity analysis described above.

Table 1: Demonstrator study descriptors: Descriptors and variants.

Once a set of descriptors and their variants has been defined, the cross-impacts of all possible combinations of descriptor-variants are assessed. For instance, the influence of global development on the price of oil was assessed as shown in Figure 2.

Figure 2: Impact assessment of descriptor A (Global development) on descriptor E (Political priority). The assessment uses an ordinal qualitative judgment scale from -3, 0, to +3, meaning strong/medium/weak inhibiting influence, no influence, to weak/medium/strong promoting influence. The judgment +3 in the bottom right corner of the judgment section expresses the judgment that severely confrontational global development would strongly promote rapid growth in oil prices.

Preparing impact assessments as shown in Figure 2 for each pair of descriptors defines a qualitative impact network for the context system (see Table A.2 in the appendix). It can be evaluated using the CIB algorithm, which scans all possible configurations of descriptor futures and assesses their internal consistency. A configuration is rated to be valid (i.e. internally consistent), if no descriptor is able to improve the weighted sum of its incoming impacts by changing its assigned future. This criterion ensures that supporting impacts dominate the relations between the elements of the configuration, thus producing a network of mutually supportive assumptions. Free software ("ScenarioWizard") to execute the algorithm is available at [72].

In the case of the demonstrator data, the evaluation yields 25 consistent scenarios. The complete list is documented in the appendix (Table A.3). Table 3 shows a selection of four scenarios in order to demonstrate the diversity of the resulting context stories (denoted as scenarios 4, 10, 15 and 24 in the full list).

Table 2: Examples of consistent context scenarios in the demonstrator study. See appendix for a full list of 25 scenarios.

Narratives explaining the context scenarios shown in Table 3 can be constructed by reading and interpreting the impact relations between the scenario elements, documented in the cross-impact matrix. Short narratives about the selected scenarios are:

S4 “Revolution from above”: While global development is showing convergence and prosperity, the oil price grows moderately. Germany achieves medium economic growth, which is sufficient to enable necessary investments. This helps keep the energy transition at the top of the political agenda. Planning legislation is advanced in order to speed up the transition. However, lack of participation causes skepticism in the population towards renewables and associated infrastructural modifications including those intended to maintain security of supply. A gap arises between the strong ambitions of the government – which adheres to its goals, motivated by strong climate change signals - and a reluctant, disappointed population. It is this gap that lends the scenario its central motif and its title. As a consequence, the private sector contributes only very little to the energy transition and, in the wake of infrastructure restrictions, energy security decreases.

S10 “Consensus in a supporting environment”: This scenario shows a tendentially supportive combination of variants regarding the prosperity of the energy transition. Once again, global development is showing convergence and prosperity. The oil price grows only moderately. Germany achieves medium economic growth, which enables necessary investment costs and – together with the motivation coming from clearly visible regional climate change signals - helps keep the energy transition at the top of the agenda. In contrast to the previous scenario, politicians successfully promote the energy transition by offering means of participation and avoid estrangement with the population in this policy field. Industry and private households invest in new, energy efficient technologies. As a result the fast extension of both renewable energy technologies and infrastructures such as storages and the electricity grid is supported, maintaining a high level of security of supply. This scenario corresponds to the framework assumptions of the reference scenario in paragraph 5.3.

S15 “It’s the economy, stupid”: The gap in economic growth between the stagnant economy in developing countries and strong economic growth in industrial countries is getting wider in this scenario. This divergence means that the boost to economic growth brought by the impact of globalization is decreasing in Germany. As a consequence, economic growth tops the political agenda (giving the scenario its title, citing a famous mot of Bill Clinton’s election campaign in 1992). Investment friendly legislation, an only slightly decreasing population (a prosperous Germany proving attractive to migrants), not to mention low oil prices – resulting from low demand in the developing countries – all help realize strong economic growth in Germany. With regard to the energy transition, this environment is rather limiting. The low oil price, a government absorbed by economic issues, and incoherent planning legislation render many investments in renewables and energy efficiency unprofitable. Challenges to security of supply are limited in this scenario.

S24 “Stormy waters ahead”: This scenario clearly shows the least happy society. Economic and political imbalance between the regions of the world generates political conflicts, resulting in a rapidly growing oil price and weak economic growth in Germany (the latter also being slowed by a dramatically decreasing population). Security becomes the top concern for the government and the public. The envisioned energy transition project is downscaled to a project of national energy security instead of environmental protection. Planning legislation is advanced in order to promote the increase of the share of renewables, which is tolerated by the population following a public consensus (driven by deep concerns about coming threats) that gives collective needs priority over individual rights. This ensures security of supply in its technical dimension whereas energy security in its political meaning is low in this scenario. Industry makes a concerted effort to save energy in a move to cushion the effects of high energy prices. As the effects of climate change are less apparent than in the other scenarios, and concerns about the environment are rated to be less important, skepticism among the population towards the energy transition in its former meaning is strong. Despite strong price signals, the tight budgets associated with a slowly growing economy and an unwillingness to relinquish savings in times of uncertainty limit investment in energy efficiency as well as in renewables in many households.

The resulting final energy consumption and energy related CO_2 emissions were calculated for all 25 consistent context scenarios. In contrast to the traditional approach (sensitivity tests for *single* parameters), the context scenario approach generally requires the simultaneous variation *of the characteristics of several* descriptors. This is because the variation of a single descriptor would often (though not necessarily) result in an inconsistent scenario. Figure 3 shows the results for all consistent context scenarios (note that some context scenarios differ only in descriptors without direct influence on energy demand and CO2 emissions. Some data points in Figure 3 therefore represent more than one context scenario).

Figure 3: Sensitivity of model results to storyline variation.

It can be clearly seen that changing the storyline can have a dramatically larger impact on the model results than changing a single input parameter. Some aspects worthy of emphasis:

Feasibility of the 'Energiewende'

Although the range of possible futures for each descriptor was restricted to clearly possible developments (thereby excluding extreme assumptions), and the CIB algorithm rigorously cut down the space of possible combinations to a very small subset of highly plausible configurations (in the demonstrator example: 25 out of 139,968), the results spread from total success to total failure in terms of the targets of the "Energiewende". By elaborating which types of political, economic and societal framework assumptions justify a positive answer and which do not, the proposed approach delivers far richer policy advice concerning the question as to whether the goals of the German 'Energiewende' are feasible.

Role of economic growth

By also considering the potential impact on other fields, the socio-technical scenario approach goes a step further than sensitivity analysis when it comes to assessing the role of economic growth. The result - in this demonstrator analysis - was that none of the sensitivity test cases shown in Figure 2 appear in the list of consistent context scenarios. This indicates that if the assumption on GDP is varied, other assumptions must be changed as well in order to keep the storyline consistent. This accounts for side effects in the assumed change in GDP. In the demonstrator the minimum secondary change required to keep the storyline consistent after increasing GDP growth, was to select a higher population (as a consequence of Germany now being more attractive to migrants). This indirect effect intensifies the impact of high economic growth beyond the effect indicated by sensitivity analysis.

Even more striking was the difference between sensitivity analysis and context scenario based analysis in the case of a weak economy. The weak-economy storyline closest to the reference scenario (S5) describes a loss of public acceptance of the energy goals (people resenting additional household costs and burdens on the economy) and, in consequence, an only moderate extension of renewables, a slower building renovation rate, and frictions when implementing new mobility structures. As a consequence, energy demand and CO_2 emissions are not reduced in comparison with the reference scenario, *but increased*, a contradiction to the results of the sensitivity analysis not only in strength, but also with regard to the direction of impact.

The (illustrative) policy advice, derived from the context scenario analysis, therefore differs from the one derived by the sensitivity analysis:

> "*The effect of economic growth on energy goals depends heavily on the circumstances. Neither strong nor medium nor weak growth prevents or guarantees moderate success. The best results, however, can be demonstrated in cases with medium economic growth.*"

The demonstrator exercise, despite its simplicity, shows that a deficit in the traditional approach arises due to the fact that it does not guarantee the consistency of its framework assumptions, but assumes that robust conclusions can be drawn from an analysis regarding each energy system driver as an isolated factor. It thus ignores the complex interplay between different drivers, potentially resulting in quantitatively and qualitatively wrong conclusions. The classical setup process for defining model assumptions generally does not undergo systematic consistency checks, which is now explicitly included through the approach presented in this paper.

6. Discussion

Applying SAS-approaches in energy scenario construction promises significant methodological improvements, as has been previously observed by several researchers (cf. chapter 3.3). The basic advantage is described in Chapter 6.1.

6.1 Account of input data uncertainty in energy modeling

Storylines rather than fixed sets of framework assumptions address the fact that many framework assumptions are deeply uncertain (particularly in the long term), and that the effect of changing an isolated assumption critically depends on the story behind the change. In this respect they are superior also to sensitivity analysis, which addresses parameter uncertainty as well but focuses on the effects of single parameter variations. Drawing conclusions from energy scenarios without challenging their results by comprehensively accounting for their input uncertainty may easily lead to overconfidence in the conclusions - and the policy advice derived therefrom. Storyline approaches instead of the random variation of input assumptions help to focus on a small and feasible number of highly relevant test cases, excluding implausible variations. The approach does not *reduce* input data uncertainty - but it helps to adequately *represent* input data uncertainty in the analysis.

For the following reasons, substituting 'intuitive logics' (IL) with the CIB method in SAS can improve the approach still further:

6.2 Storyline quality

The first advantage of combining "CIB and Simulation" [26] is that the complexity of the embedding system and the uncertainty of model input data are better addressed and captured. As CIB can be applied via software and creates storylines using an algorithm, system boundaries need not be narrowed down to a very few interdependent factors capable of being handled by intuitive scenario construction. This can be realized with the CIB method because it is not dependent on the limited capability of the human mind; instead it processes multiple interdependencies at the same time [31]. Secondly, by using the more systematic CIB-based approach, analysts are better able to ensure input data set consistency and plausibility.

6.3 Traceability of storyline construction

An additional benefit of using CIB as a storyline generator is that the qualitative part of SAS is strengthened by improvements in traceability and objectivity [34], because any assumptions relating to complex societal developments and the framework for the model are explicitly addressed and revealed.

6.4 Range of considered possible futures

Moreover, scenario content is enriched due to the inclusion of a higher number of descriptors in the analysis, making the adequacy of storylines easier to ensure, which means that the space of possible context futures is screened more exhaustively. By systematically developing traceable and transparent impact networks (in an impact matrix) for the system under consideration, storyline revisions and updates become easier, or even simply possible. Another advantage is associated with the use of a systematic approach, namely the ability to produce a high number of storylines, if requested, due to the algorithmic nature of generation [35]. Combining a context scenario analysis based on a high number of storylines with methods aiming at output-focused structuring, e.g. Scenario Discovery [73] may offer additional advantage.

6.5 Reflections about model adequacy supported

In many studies, the question whether a new quantitative model design is needed for energy systems analysis is not systematically answered. Instead, existing models are often adopted and employed. At this juncture, the context scenario approach supports a checkup if the model design provides an adequate response to the research question: In cases where the context scenarios point to critical socio-technical interactions and the technical part thereof cannot be analyzed by the model because of structural limitations, an expansion or a replacement of the model can be considered.

A special situation arises if more than one model is to be applied in complex analysis tasks and the context scenarios are developed as a common context information for all models. The context scenarios then can serve as a coherence test: Difficulties in getting the common context scenarios consistent with each of the model exercises indicate possible coherence problems between the models or their data.

Despite these improvements, the approach of CIB-based construction of socio-technical energy scenarios still has its own limitations (see also [26]). They are described in the following paragraphs.

6.6 Resource requirements

One disadvantage of the context scenario approach is that it necessitates a separate scenario exercise in addition to the model exercise, thus taking extra time, method expertise and resources. The potential for adapting the method within short and small scenario projects may therefore be limited. Generally, resource requirements make it necessary to restrict the number of descriptors typically considered in the context scenarios to 10-20 factors (however, examples of considerably larger context scenario exercises exist, e.g. [51]). This means the typical sized analysis, though more complete than other approaches, still does not cover all major system parameters.

6.7 Retaining intuitive and subjective influences in storyline construction

Although CIB-based storyline construction - generating storylines per algorithm - is far more systematic than traditional “Intuitive logics”-based approaches, the method still incorporates some intuitive steps such as expert judgments, the compilation of descriptors, quantification of descriptor definitions, not to mention the final selection of scenarios, or the interpretation of the raw scenarios. This drawback needs to be alleviated by selecting the contributing experts carefully and by a careful documentation of assumptions (e.g. behind impact assessments) and decisions (e.g. during scenario selection and interpretation). Significant expert dissent about impact assessments, which can occur during the preparation of the cross-impact matrix, should be documented and represented by evaluating several matrix variants. However, the method requires that strong expert dissent is limited to few topics. If dissent generally dominates the experts views, a CIB analysis (and probably also many other systems analysis approaches) become unmanageable.

6.8 Limited capability of representing temporal complexity

CIB leads to context scenarios based on reflections about the interdependences between predefined alternative developments in different fields. The alternative futures can be defined in a dynamic sense, such as ‘growing by 1% per year’ or ‘oscillating within a 10-year period’. But once defined, the dynamic description of the future variants cannot be varied ‘in the runtime’ of the analysis. This limits the capacity of the method for analyzing processes highly structured on the timeline.

6.9 Separate analysis of societal and technical matters

The context scenario concept enables a better inclusion of societal matters in energy model analysis. However, this is done by supplementing the model analysis with a separate analysis of the embedding system, thus perpetuating the conceptual separation of technical and societal “spheres”. More ambitious visions of socio-technical analysis may well claim the desirability of a genuinely fused analysis of societal and technical processes, and from this perspective, the context scenario approach may be regarded as a step in the right direction, but not as a fundamental solution. From a pragmatic point of view, however, the concept enables a socio-technical analysis based on current energy models existing today with their immense treasure of methods and data, while avoiding the necessity of waiting for the development of desirable, yet to be created energy models with genuine amalgamation of societal and technical process analysis.

7. Conclusions

The focus of this article was on the influence of framework condition uncertainty on the robustness of model based energy scenario analysis. According to the analysis described before, applying the Story-and-Simulation concept known from environmental and climate modeling can improve the quality of the outcome of scenario analysis, in particular if the storylines are constructed using systematic (formalized) scenario methods. By using the CIB scenario method as a storyline generator, the concept's ability to deal with highly diverse input data sets, representing context uncertainty and complexity in a systematic and traceable manner was demonstrated. The finding is that the context scenario approach can be seen as a well-balanced middle course in sensitivity analysis: compared with single-parameter-variation analysis it avoids underestimating the impact of parameter uncertainty by varying complete storylines instead of isolated parameters. Compared with random-based multi-parameter-variation analysis (Monte-Carlo analysis) the approach avoids overestimating output uncertainty because the consistency condition eliminates meaningless sets of input parameter variations lacking justification by a plausible story. In summary, the context scenario approach should contribute to the improvement of model based energy scenario analysis in the following areas:

- The approach offers a particularly systematic and traceable procedure for promoting consistency in framework assumptions;
- The approach supports a more consistent estimation of the influence of framework assumption uncertainty on the robustness of model results and conclusions derived thereof;
- Overall, the approach fosters a stronger socio-technical perspective of model-based energy scenario analysis and increases the understanding of the interplay between societal and energy-related developments.

On the other hand, there are also several restrictions of the concept caused by its significant resource requirements and the rather pragmatic way it approaches the far-reaching vision of socio-technical analysis - the context scenario concept is clearly not a panacea for all the problems limiting the significance and validity of energy scenarios. However, based upon the authors' experience so far, it definitely moves towards counteracting one current weakness of energy scenario construction – the high degree of disregard for context uncertainty – and is certainly worth the effort, at least when creating long term energy scenarios intended for policy-advice. Currently, several projects for constructing socio-technical energy scenarios based on the proposed approach are running in the ENERGY-TRANS Alliance and results will be published in near future. In these full-scale scenario analyses further important aspects of energy transition, such as security of supply (i.e. import dependency on fossil fuels or other resources, secure capacities installed in the electricity supply system) as well as other criteria, e.g. generation costs for heat, electricity and fuels and further economic, environmental and political aspects enhancing the scope of socio-technical scenario analysis are addressed.

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References

[1] Grunwald, A. (2011): Energy futures: Diversity and the need for assessment. In: Futures 43, 820-830. DOI: 10.1016/j.futures.2011.05.024.

[2] Prognos (2011): Analysis and comparison of relevant mid- and long-term energy scenarios for EU and their key underlying assumptions. Prognos AG, Bases (Switzerland). URL: http://www.prognos.com/uploads/tx_atwpubdb/110427_Prognos_EU_Energy_Scenarios.pdf (accessed on August 3rd, 2015).

[3] KIT (2016): ENERGY-TRANS. URL: http://www.energy-trans.de (accessed on March 20th, 2016).

[4] Börjeson, L.; Höjer, M.; Dreborg, K.-H.; Ekvall, T.; Finnveden, G. (2006): Scenario types and techniques: Towards a user´s guide. In: Futures 38, 723-739. DOI: 10.1016/j.futures.2005.12.002.

[5] Blesl, M.; Kober, T.; Kuder, R.; Bruchof, D. (2012): Implications of different climate policy protection regimes for the EU - 27 and its member states through 2050. In: Climate Policy 12(3), 301–319. DOI:10.1080/14693062.2011.637815.

[6] Burniaux, J.-M.; Truong, P. T. (2002): GTAP-E - An Energy-Environmental Version of the GTAP Model. GTAP Technical Paper No. 16. URL: https://www.gtap.agecon.purdue.edu/resources/download/1203.pdf (accessed on September 4th, 2015).

[7] IEA (2013): World Energy Outlook 2013. OECD/IEA, Paris (France). URL: http://www.worldenergyoutlook.org/publications/weo-2013/ (accessed on April 1st, 2016).

[8] UNPD (2013): World Population Prospects: The 2012 Revisions. United Nations Population Division, New York (USA). URL: http://esa.un.org/unpd/wpp/Publications/ (accessed on August 11th, 2015).

[9] IEA (2012): Energy Technology Perspectives. IEA/OECD, Paris (France). URL: http://www.iea.org/publications/freepublications/publication/WEO2012_free.pdf (accessed on August 3rd, 2015).

[10] Alcamo, J. (2008): Chapter Six. The SAS Approach: Combining Qualitative and Quantitative Knowledge in Environmental Scenarios. In: Alcamo, J. (Ed.): Environmental Futures - The Practice of Environmental Scenario Analysis. Elsevier, Amsterdam (the Netherlands), Volume 2, 123–150. ISBN 9780444532930. DOI: 10.1016/S1574-101X(08)00406-7.

[11] Mai, T.; Logan, J.; Blair, N.; Sullivan, P.; Bazilian, M. (2013): RE-ASSUME- A Decision Maker's Guide to Evaluating Energy Scenarios, Modeling, and Assumptions. National Renewable Energy Laboratory, Golden, CO (USA). URL: http://iea-retd.org/wp-content/uploads/2013/07/RE-ASSUME_IEA-RETD_2013.pdf (accessed on July 27th, 2015).

[12] Alcamo, J. (2001): Scenarios as tools for international environmental assessments. Experts' corner report, Prospects and Scenarios No 5. European Environment Agency, Copenhagen (Denmark). ISBN 92-9167-402-8.

[13] Forrester, J. W. (1979): World dynamics. Wright-Allen Press, Cambridge, Mass. (USA.), 2nd edition. ISBN-13: 978-1563270598.

[14] Checkland, P. (2000): Soft Systems Methodology: A Thirty Year Retrospective. In: Systems Research and Behavioral Science 17, 11-58. DOI: 10.1002/1099-1743(200011)17:1+<::AID-SRES374>3.0.CO;2-O.

[15] Döll, P.; Krol, M. S. (2002): Integrated scenarios of regional development in two semi-arid states of north-eastern Brazil. In: Integrated Assessment 3 (4), 308–320. DOI: 10.1076/iaij.3.4.308.13588.

[16] Kemp-Benedict, E. (2004): From narrative to number: A role for quantitative models in scenario analysis. In: Pahl-Wostl, C. et al. (eds.): Complexity and Integrated Resources Management. Transactions of the 2nd

Biennial Meeting of the iEMSs. International Environmental Modelling and Software Society (Vol 2), 765–770. URL: http://www.iemss.org/iemss2004/pdf/scenario/kempfrom.pdf pdf (accessed on July 27th, 2015).

[17] Winterscheid, A. (2008): Scenario technique in flood risk management (in German). PhD-thesis. Reports of the Institute for Hydraulic Engineering Vol. 143, Tech. University of Darmstadt (Germany). ISBN 978-3-936146-22-6.

[18] Rounsevell, M.; Metzger, M. (2010): Developing qualitative scenario storylines for environmental change assessment. In: Wiley Interdisciplinary Reviews: Climate Change 1 (4), 606–619. DOI: 10.1002/wcc.63.

[19] Gallopin, G. C.; Rijsberman, F. (2000): Three global water scenarios. In: International Journal of Water 1 (1), p. 16. DOI: 10.1504/IJW.2000.002055.

[20] Carpenter, S.; Pingali, P.; Bennett, E.; Zurek, M. (Eds.) (2005): Millennium Ecosystem Assessment. Volume 2 Scenarios Assessment. Island Press, Washington, D.C. (USA). ISBN 1-55963-390-5.

[21] UNEP (2007): Global Environmental Outlook 4. Environment for Development. United Nations Environment Programme, Nairobi (Kenya). ISBN: 978-92-807-2836-1.

[22] EEA (2007): Land-use scenarios for Europe: qualitative and quantitative analysis on a European scale. EEA Technical Report No 9/2007. European Environment Agency, Copenhagen (Denmark). ISBN: 987-92-9167-927-0.

[23] Nakicenovic, N.; Alcamo, J.; Davis, G. et al. (2000): Special report on emissions scenarios (IPCC SRES report). Cambridge University Press, New York (USA).

[24] Erdmann, L.; Hilty, L. (2010): Scenario Analysis. Exploring the Macroeconomic Impacts of Information and Communication Technologies on Greenhouse Gas Emissions. In: Industrial Ecology, 14 (5), 826-843. DOI: 10.1111/j.1530-9290.2010.00277.x.

[25] Böhringer, C.; Löschel, A. (2005): Climate Policy Beyond Kyoto: Quo Vadis? A Computable General Equilibrium Analysis Based on Expert Judgments. In: Kyklos 58 (4), 467–493. DOI: 10.1111/j.0023-5962.2005.00298.x.

[26] Kosow, H. (2011): Consistent context scenarios: a new approach to ‘story and simulation’. In: Proceedings of the 4th International Seville Conference on Future-Oriented Technology Analysis (FTA), Seville (Spain), May 12-13th, 2011.

[27] Weimer-Jehle, W.; Prehofer, S.; Vögele, S. (2013): Context scenarios - a concept for addressing context uncertainty and context complexity in energy scenarios (in German). In: Technikfolgenabschätzung in Theorie und Praxis 22(2), 27–36. URL: http://www.tatup-journal.de/downloads/2013/tatup132_weua13a.pdf (accessed on July 27th, 2015).

[28] Kemp-Benedict, E. (2010): Converting qualitative assessments to quantitative assumptions: Bayes' rule and the pundit's wager. In: Technological Forecasting and Social Change 77 (1), 167–171. DOI: 10.1016/j.techfore.2009.06.008.

[29] Garb, Y.; Pulver, S.; VanDeveer, S. (2008): Scenarios in society, society in scenarios: toward a social scientific analysis of storyline-driven environmental modeling. In: Environmental Research Letters 3 (4), 45015. DOI: 10.1088/1748-9326/3/4/045015.

[30] Huss, W.; Honton, E. (1987): Alternative Methods for Developing Business Scenarios. In: Technological Forecasting and Social Change (31), 219–238. DOI: 10.1016/0040-1625(87)90012-6.

[31] Weimer-Jehle, W. (2006): Cross-impact balances: a system-theoretical approach to cross-impact analysis. In: Technological Forecasting and Social Change 73, 334–361. DOI: 10.1016/j.techfore.2005.06.005.

[32] Kemp-Benedict, E. (2012): Telling better stories: strengthening the story in story and simulation. In: Environmental Research Letters 7 (4), DOI: 10.1088/1748-9326/7/4/041004.

[33] Schweizer, V.; Kriegler, E. (2012): Improving environmental change research with systematic techniques for qualitative scenarios. In: Environmental Research Letters 7 (4), 44011. DOI: 10.1088/1748-9326/7/4/044011.

[34] Lloyd, E.A.; Schweizer, V.J. (2014): Objectivity and a comparison of methodological scenario approaches for climate change research. In: Synthese, 191(10), 2049-2088. DOI 10.1007/s11229—013-0353-6.

[35] Schweizer, V.; O'Neill, B. (2014): Systematic construction of global socioeconomic pathways using internally consistent element combinations. In: Climatic Change 122, 431–445. DOI 10.1007/s10584-013-0908-z.

[36] O'Neill, B.; Kriegler, E.; Riahi, K.; Ebi, K.; Hallegatte, S., Carter, I.; Mathur, R.; van Vuuren, D.P. (2014): A new scenario framework, for climate change research: The concept of shared socioeconomic pathways. In: Climatic Change. DOI:10.1007/s10584-013-0905-2.

[37] Mander, S.L.; Bows, A.; Anderson, K.L.; Shackley, S.; Agnolucci, P.; Ekins, P. (2008): The Tyndall decarbonisation scenarios—Part I: Development of a backcasting methodology with stakeholder participation. In: Energy Policy 36, 3754-3763. DOI: 10.1016/j.enpol.2008.06.003.

[38] Anderson, K.L.; Mander, S.; Bows, A.; Shackley, S.; Agnolucci, P.; Ekins, P. (2008): The Tyndall decarbonisation scenarios—Part II: Scenarios for a 60% CO_2 reduction in the UK. In: Energy Policy 36, 3764-3773. DOI: 10.1016/j.enpol.2008.06.002.

[39] Spangenberg, J. H. (2007): Integrated scenarios for assessing biodiversity risks. In: International Journal of Sustainable Development 15, 343–356. DOI: 10.1002/sd.331.

[40] Stocker, A.; Omann, I.; Jäger, J. (2012): The socio-economic modelling of the ALARM scenarios with GINFORS: results and analysis for selected European countries. In: Global Ecology and Biogeography 21, 36–49. DOI: 10.1111/j.1466-8238.2010.00639.x.

[41] CLUES (2012): Learning Through Scenarios: Exploring the Future of Decentralised Energy in the UK. Sussex Energy Group, Policy briefing, Brighton (UK). URL: http://www.ucl.ac.uk/clues/files/scenarios_briefing (accessed on August 25th, 2015).

[42] Gouveia, J.P.; Fortes, P.; Seixas, J. (2012): Projections of energy services demand for residential buildings: Insights from a bottom-up methodology. In: Energy 47, 430-442. DOI: 10.1016/j.energy.2012.09.042.

[43] van Vuuren, D.P.; Kok, M. T. J.; Giod, B.; Lucas, P. L.; de Vries, B. (2012): Scenarios in Global Environmental Assessments - Key characteristics and lessons for future use. In: Global Environmental Change 22, 884–895. DOI: 10.1016/j.gloenvcha.2012.06.001.

[44] Capellán-Pérez, I.; Mediavilla, M.; de Castro, C; Carpintero, Ó.; Miguel, L.J. (2014): Fossil fuel depletion and socio-economic scenarios - An integrated approach. In: Energy, 77, 641-555. DOI: 10.1016/j.energy.2014.09.063.

[45] SHELL (2013): New Lens Scenarios. Royal Dutch Shell, The Hague (The Netherlands). URL: http://s01.static-shell.com/content/dam/shell-new/local/corporate/Scenarios/Downloads/Scenarios_newdoc.pdf (accessed on August 11th, 2015).

[46] O'Mahony, T. (2014): Integrated scenarios for energy: A methodology for the short term. In: Futures, 55, 41-57. DOI: 10.1016/j.futures.2013.11.002.

[47] O'Mahony, T.; Zhou, P.; Sweeney, J. (2013): Integrated scenarios of energy-related CO2-emissions in Ireland: A multi-sectoral analysis to 2020. In: Ecological Economics, 93, 385-397. DOI: 10.1016/j.ecolecon.2013.06.016.

[48] Trutnevyte, E.; Barton, J.; O'Grady, A.; Ogunkunle, D.; Pudjianto, D.; Robertson, E. (2014): Linking a storyline with multiple models - A cross-scale study of the UK power system transition. In: Technological Forecasting & Social Change 89, 26-42. DOI: 10.1016/j.techfore.2014.08.018.

[49] McDowall, W. (2014): Exploring possible transition pathways for hydrogen energy: A hybrid approach using socio-technical scenarios and energy system modeling. In: Futures 63, 1–14. DOI 10.1016/j.futures.2014.07.004.

[50] Fortes, P.; Alvarenga, A.; Seixas, J.; Rodrigues, S. (2015): Long-term energy scenarios: Bridging the gap between socio-economic storylines and energy modeling. In: Technological Forecasting & Social Change 91, 161–178. DOI: 10.1016/j.techfore.2014.02.006.

[51] Hansen, P.; Pannaye, C.; Vögele, S.; Weimer-Jehle, W.; Prehofer, S.; Poganietz, W.-R. (2014): The Future(s) of the Energy Consumption of Private Households in Germany - A Multilevel Cross-Impact Analysis. Research Center Jülich, STE Research Report 7/2014, Jülich (Germany). URL: http://www.fz-juelich.de/SharedDocs/Downloads/IEK/IEK-STE/DE/Publikationen/research_reports/2014/report_07_2014.pdf?__blob=publicationFile (accessed on August 24th, 2015).

[52] Wachsmuth, J. (2015): Cross-sectoral integration in regional adaptation to climate change via participatory scenario development. In: Climatic Change 132, 387-400. DOI 10.1007/s10584-014-1231-z.

[53] Ruth, M.; Özgün, O.; Wachsmuth, J.; Gößling-Reisemann, S. (2015): Dynamics of energy transitions under changing socioeconomic, technological and climate conditions in Northwest Germany. In: Ecological Economics, 111, 29-47. DOI: 10.1016/j.ecolecon.2014.12.025.

[54] Weimer-Jehle, W. (2008): Applying pair interaction systems and multi-value Kauffman nets to multidisciplinary systems analysis. In: Physica A 387, 3689-3700. DOI: 10.1016/j.physa.2008.02.006.

[55] Rhyne, R. (1974): Technological Forecasting Within Whole Futures Projections. In: Technological Forecasting and Social Change, 6, 133-162. DOI: 10.1016/0040-1625(74)90014-6.

[56] Gausemeier, J.; Fink, A.; Schlacke, O. (1998): Scenario management - an approach to develop future potentials. In: Technological Forecasting and Social Change, 59, 111-130. DOI: 10.1016/S0040-1625(97)00166-2.

[57] Gordon, T.J.; Hayward, H. (1968): Initial experiments with the cross-impact matrix method of forecasting. In: Futures 1(2), 100-116. DOI: 10.1016/S0016-3287(68)80003-5.

[58] Schneider, M.; Gill, B. (2016): Biotechnology versus agroecology - Entrenchments and surprise at a 2030 forecast scenario workshop. In: Science and Public Policy 43, 74-84, DOI:10.1093/scipol/scv021.

[59] Meylan G.; Seidl R.; Spoerri A. (2013): Transitions of municipal solid waste management. Part I: Scenarios of Swiss waste glass-packaging disposal. In: Resources, Conservation and Recycling 74, 8-19. DOI: 10.1016/j.resconrec.2013.02.011.

[60] Jenssen T.; Weimer-Jehle W. (2012): More than the Sum of Its Parts. Consistent Scenarios for the Consumption of Heat Energy as a Common Reference Point for Policy and Science. In: GAIA 21/4, 290–299.

[61] Weimer-Jehle, W.; Wassermann, S.; Kosow, H. (2011): Consistent framework assumptions for modelling and scenario building at the Federal Environmental Agency (in German). Report to the German Federal Environmental Agency (UBA). UBA-Texte 20/2011, Dessau-Roßlau (Germany). URL: http://www.uba.de/uba-info-medien/4096.html (accessed on August 11th, 2015).

[62] Weimer-Jehle, W.; Deuschle, J.; Rehaag, R. (2012): Familial and societal causes of juvenile obesity - a qualitative model on obesity development and prevention in socially disadvantaged children and adolescents. In: Journal of Public Health 20(2), 111-124. DOI: 10.1007/s10389-011-0473-8.

[63] Fuchs, G.; Fahl, U.; Pyka, A.; Staber, U.; Vögele, S.; Weimer-Jehle, W. (2008): Generating Innovation Scenarios using the Cross-Impact Methodology. Department of Economics, University of Bremen, Discussion-Papers Series No. 007-2008, Bremen (Germany). URL: http://www.cross-impact.de/Ressourcen/generating_innovation_scenarios.pdf (accessed on July 27th, 2015).

[64] Kemp-Benedict, E.; de Jong, W.; Pacheco P. (2014): Forest futures: Linking global paths to local conditions. In: Katila, P.; Galloway, G.; de Jong, W.; Pacheco, P.; Mery, G. (eds.): Forest under pressure - Local responses to global issues. Part IV - Possible future pathways. IUFRO World Series Vol. 32, IUFRO, Vienna (Austria). ISBN 978-3-902762-30-6.

[65] ZIRIUS (2016a): Cross-Impact Balance Analysis: Bibliography. URL: http://www.cross-impact.de/english/CIB_e_Pub.htm. (accessed on March 20th, 2016).

[66] Honton, E.J.; Stacey, G.S.; Millett, S.M. (1985): Future Scenarios - The BASICS Computational Method. Economics and Policy Analysis Occasional Paper No. 44, Batelle Columbus Division, Columbus, Ohio (USA).

[67] Amer, M.; Daim, T.U.; Jetter, A. (2013): A review of scenario planning. In: Futures 46, 23-40. DOI: 10.1016/j.futures.2012.10.003.

[68] Pregger, T.; Nitsch, J.; Naegler, T. (2013): Long-term scenarios and strategies for the deployment of renewable energies in Germany. In: Energy Policy, 59, pp. 350-360. DOI: 10.1016/j.enpol.2013.03.049.

[69] Schlesinger, M.; Hofer, P.; Kemmler, A.; Kirchner, A.; Strassburg, S.; Lindenberger, D.; Fürsch, M., Nagl, S.; Paulus, M.; Richter, J.; Trüby. J.; Lutz, C.; Khorushun, O.; Lehr, U.; Thobe, I. (2010): Energy scenarios for an energy concept of the Federal Government (in German). Report to the Federal Ministry for Economy and Technology (BMWi). Prognos AG Basel (Switzerland), EWI, GWS. URL: http://www.ewi.uni-koeln.de/fileadmin/user_upload/Publikationen/Studien/Politik_und_Gesellschaft/2010/EWI_2010-08-30_Energieszenarien-Studie.pdf (accessed on August 3rd, 2015).

[70] Nitsch, J.; Pregger, T.; Naegler, T.; Heide, D.; Luca de Tena, D.; Trieb, F.; Scholz, Y.; Nienhaus, K.; Gerhard, N.; Sterner, M.; Trost, T.; von Oehsen, A.; Schwinn, R.; Pape, C.; Hahn, H.; Wickert M.; Wenzel B. (2012): Long-term scenarios and strategies for the deployment of renewable energies in Germany under consideration of European and global developments (in German). Report to the German Federal Ministry for the Environment (BMU). DLR Stuttgart (Germany), FhG IWES, IfnE. ULR: http://www.dlr.de/dlr/Portaldata/1/Resources/bilder/portal/portal_2012_1/leitstudie2011_bf.pdf (accessed on August 3rd, 2015).

[71] BMWi (2010): Energy concept for an environmental-friendly, reliable and affordable energy supply (in German). Federal Ministry for Economy and Technology (BMWi), Berlin (Germany). URL: http://www.bundesregierung.de/ContentArchiv/DE/Archiv17/_Anlagen/2012/02/energiekonzept-final.pdf?__blob=publicationFile&v=5 (accessed on August 9th, 2015).

[72] ZIRIUS (2016b): ScenarioWizard. Software for constructing consistent scenarios using Cross-Impact Balance Analysis. URL: http://www.cross-impact.de/english/CIB_e_ScW.htm (accessed on March 20th, 2016).

[73] Gerst, M.D.; Wang, P.; Borsuk, M.E. (2013): Discovering plausible energy and economic futures under global change using multidimensional scenario discovery. In: Environmental Modelling & Software 44, 76-86. DOI: 10.1016/j.envsoft.2012.09.001.

[74] EIA (2013): International Energy Outlook 2013. U.S. Energy Information Administration (EIA), Washington D.C. (USA). URL: http://www.eia.gov/forecasts/archive/ieo13/pdf/0484%282013%29.pdf (accessed on August 4th 2015).

[75] ECF (2010): Roadmap 2050. European Climate Foundation, Brussels (Belgium). URL: http://www.roadmap2050.eu/attachments/files/Volume1_fullreport_PressPack.pdf (accessed on August 10th, 2015).

[76] WEC (2013): World Energy Scenarios - Composing energy futures to 2050. World Energy Council, London (UK). ISBN: 978 0 946121 33 5.

[77] E3M-LAB, IIASA & EUROCARE (2014): EU Energy, Transport and GHG Emissions - Trends to 2050. Publications Office of the European Union, Luxembourg (Luxembourg). ISBN 978-92-79-33728-4, DOI: 10.2833/17897.

[78] Greenpeace; EREC; GWEC (2012): Energy [R]evolution. Greenpeace International, European Renewable Energy Council (EREC), Global Wind Energy Council (GWEC). ISBN: 978-90-73361-92- 8. URL: http://www.greenpeace.org/international/Global/international/publications/climate/2012/Energy%20Revolution%202012/ER2012.pdf (accessed on August 4th, 2015).

[79] ExxonMobil (2014): The Outlook for Energy: A View to 2040. Exxon Mobil Corporation, Irving, Texas (USA). URL: http://corporate.exxonmobil.com/en/energy/energy-outlook/download-the-report/download-the-outlook-for-energy-reports (accessed on August 10th, 2015).

[80] OECD (2013), OECD Economic Outlook, Vol. 2013/1. OECD Publishing, Paris (France). http://dx.doi.org/10.1787/eco_outlook-v2013-1-en.

[81] IEA (2011): World Energy Outlook 2011. OECD/IEA, Paris (France). URL: http://www.iea.org/publications/freepublications/publication/weo2011_web.pdf (accessed on August 3rd, 2015).

[82] Oxford Economics (2012): Oxford Economic Model. URL: http://www.oxfordeconomics.com (accessed on July 27th, 2015).

[83] IEA (2009): World Energy Outlook 2009. OECD/IEA, Paris (France). URL: http://www.worldenergyoutlook.org/media/weowebsite/2008-1994/weo_2007.pdf (accessed on August 3rd, 2015).

[84] IHS Global Insight (various years): World Overview. URL: http://www.ihsglobalinsight.com (accessed on July 27th, 2015).

[85] McKinsey (2009): Pathway to a low-Carbon Economy - Version 2 of the Global Greenhouse Gas Abatement Cost Curve. McKinsey & Company. URL: http://www.mckinsey.com/~/media/mckinsey/dotcom/client_service/sustainability/cost%20curve%20pdfs/pathways_lowcarbon_economy_version2.ashx (accessed on August 11th, 2015).

[86] ECFIN (2012): The 2012 Ageing Report. European Commission - Directorate-General for Economic and Financial Affairs, Brussels (Belgium). URL: http://ec.europa.eu/economy_finance/publications/european_economy/2015/pdf/ee3_en.pdf (accessed on August 10th, 2015).

[87] International Monetary Fund (2013): World Economic Outlook: Transitions and Tensions. IMF, Washington D.C. (USA). URL: http://www.imf.org/external/pubs/ft/weo/2013/02/pdf/text.pdf (accessed on August 3rd, 2015).

Appendix

Table A.1: Examples for Energy Scenarios

Table A.2: Cross-Impact data used for the demonstrator analysis.

Table A.3: 25 context scenarios identified by CIB analysis. For explanation see Table 2. Non-numerical scenario sequence, optimized for compacted representation.

Figures and tables

Table 1: Selected results of reference scenario calculations. Goals relevant to the calculations relating to the German 'Energiewende' by 2040 are: -70% greenhouse gas emissions 1990-2040, 45 % share of renewables in final energy demand, 65 % share of renewables in electricity production, 0 % nuclear power in 2022 [71].

	Unit	*2010*	*2040*	*Goals*
Total final energy consumption	PJ/a	9 060	5 560	-
RES production (power, heat, biofuels)	PJ/a	991	2 800	45% TFE[1]
Energy-related CO_2 emissions	Mt/a	778	245	225
RES share power generation	%	16.5%	63.6%	65%
Nuclear power generation	TWh/a	140.6	0	0

[1] TFE: Total Final Energy Demand

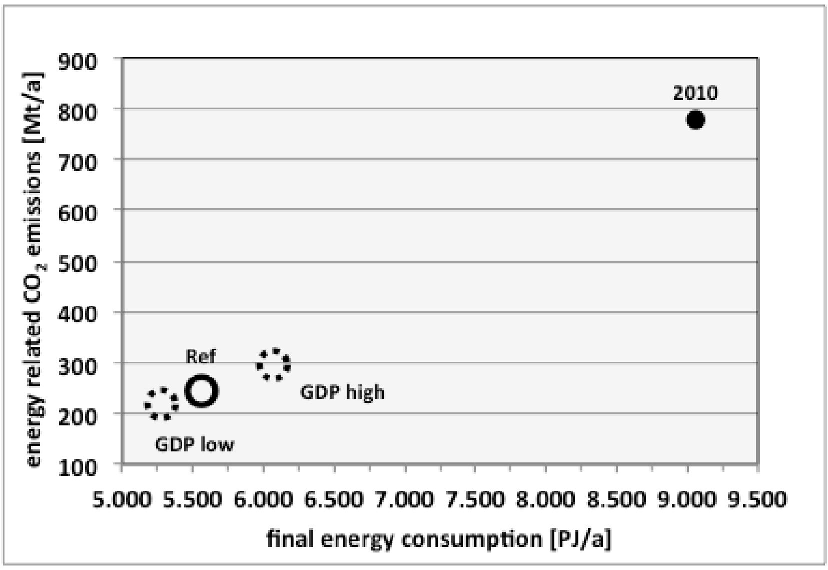

Figure 1: Sensitivity test for GDP. Reference scenario: closed circle. Results for modified GDP assumptions: open circles. Data show model results for German final energy consumption and energy related CO_2 emissions in 2040.

Table 2: Demonstrator study descriptors: Descriptors and variants.

Descriptors	*Variants*		
	1	*2*	*3*
A. Global development	convergence and prosperity	divergence	confrontation
B. Oil price	stability	medium growth	rapid growth
C. Population	slowly decreasing	strongly decreasing	-
D. Economic growth	weak	medium	strong
E. Political priority	energy turnaround	security	economy
F. Acceptance energy turnaround	skepticism	approval	-
G. Planning legislation	incoherent	promoting speed	promoting participation
H. Infrastructure extension	slow	fast	-
I. Growth of renewable energies	slow	medium	fast
J. Domestic energy savings	small	strong	-
K. Industrial energy savings	small	strong	-
L. Mobility	persistent structures	downscaling	downscaling and e-cars
M. Climate change	strong	moderate	-

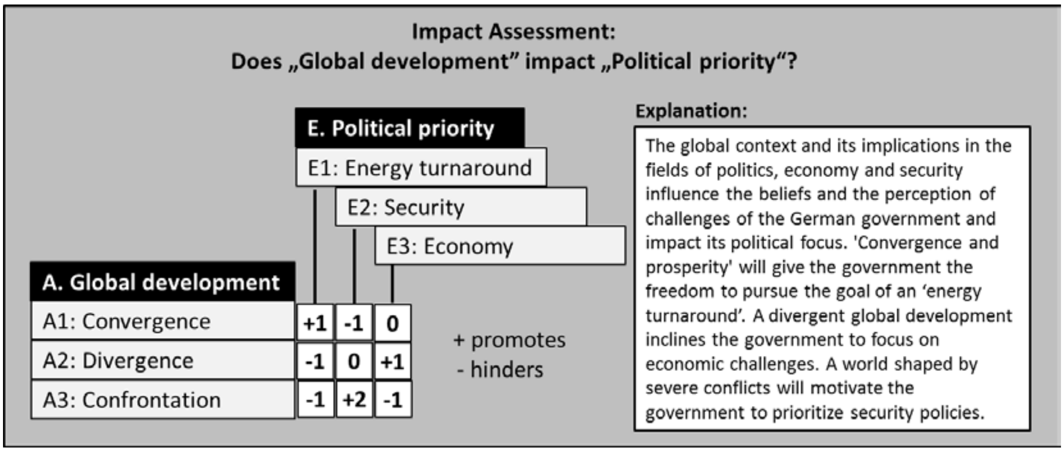

Figure 2: Impact assessment of descriptor A (Global development) on descriptor E (Political priority). The assessment uses an ordinal qualitative judgment scale from -3, 0, to +3, meaning strong/medium/weak inhibiting influence, no influence, to weak/medium/strong promoting influence. The judgment +3 in the bottom right corner of the judgment section expresses the judgment that severely confrontational global development would strongly promote rapid growth in oil prices.

Table 3: Examples of consistent context scenarios in the demonstrator study. See appendix for a full list of 25 scenarios.

<table>
<tr><th>S4 Revolution from above</th><th>S10 Consensus in a supporting environment</th><th>S15 It's the economy, stupid</th><th>S24 Stormy waters ahead</th></tr>
<tr><td colspan="2">A. Global development:
A1 convergence and prosperity</td><td>A. Global development:
A2 divergence</td><td>A. Global development:
A3 confrontation</td></tr>
<tr><td colspan="2">B. Oil price:
B2 medium growth</td><td>B. Oil price:
B1 stability</td><td>B. Oil price:
B3 rapid growth</td></tr>
<tr><td colspan="2">C. Population:
C2 strongly decreasing</td><td>C. Population:
C1 slowly decreasing</td><td>C. Population:
C2 strongly decreasing</td></tr>
<tr><td colspan="2">D. Economic growth:
D2 medium</td><td>D. Economic growth:
D3 strong</td><td>D. Economic growth:
D1 weak</td></tr>
<tr><td colspan="2">E. Political priority:
E1 energy turnaround</td><td>E. Political priority:
E3 economy</td><td>E. Political priority:
E2 security</td></tr>
<tr><td>F. Acceptance energy turnaround:
F1 scepticism</td><td>F. Acceptance energy turnaround:
F2 approval</td><td colspan="2">F. Acceptance energy turnaround:
F1 scepticism</td></tr>
<tr><td>G. Planning legislation:
G2 promoting speed</td><td>G. Planning legislation:
G3 promoting participation</td><td>G. Planning legislation:
G1 incoherent</td><td>G. Planning legislation:
G2 promoting speed</td></tr>
<tr><td colspan="2">H. Infrastructure extension:
H2 fast</td><td>H. Infrastructure extension:
H1 slow</td><td>H. Infrastructure extension:
H2 fast</td></tr>
<tr><td>I. Growth of renewable energies:
I2 medium</td><td>I. Growth of renewable energies:
I3 fast</td><td>I. Growth of renewable energies:
I1 slow</td><td>I. Growth of renewable energies:
I2 medium</td></tr>
<tr><td>J. Domestic energy savings:
J1 small</td><td>J. Domestic energy savings:
J2 strong</td><td colspan="2">J. Domestic energy savings:
J1 small</td></tr>
<tr><td colspan="2">K. Industrial energy savings:
K2 strong</td><td>K. Industrial energy savings:
K1 small</td><td>K. Industrial energy savings:
K2 strong</td></tr>
<tr><td>L. Mobility:
L1 persistent structures</td><td>L. Mobility:
L3 downscaling and e-cars</td><td>L. Mobility:
L1 persistent structures</td><td>L. Mobility:
L2 downscaling</td></tr>
<tr><td colspan="2">M. Climate change:
M1 strong</td><td colspan="2">M. Climate change:
M2 moderate</td></tr>
</table>

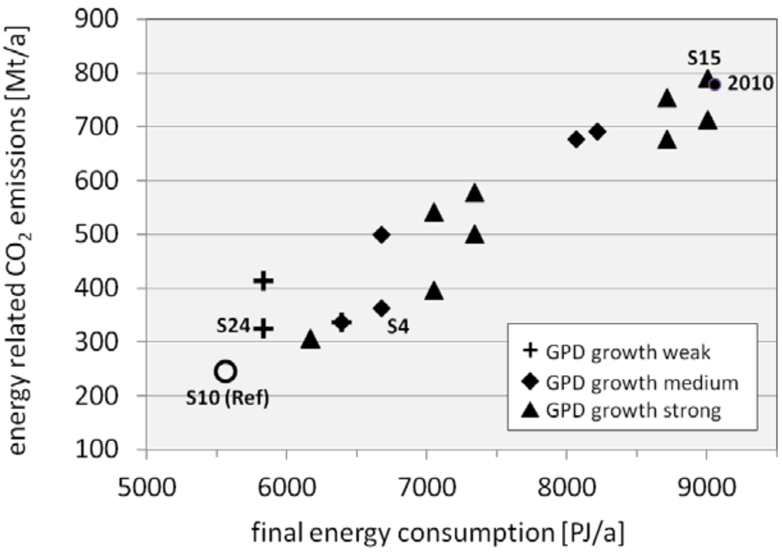

Figure 3: Sensitivity of model results to storyline variation.

Table A.1: Examples for Energy Scenarios

Study	Scenarios	Key Factors – Source used				Analyses of interactions
		Growth of GDP	Population	Oil Price	CO2-Policy	
IEA – World Energy Outlook [7]	• Current Policies Scenario • New Policies Scenario • 450 Scenario	[80], [87], own calc. based on changes in labor supply and improve. in productivity	[8]	own calculations taking changes in energy demand into account	own compilation	use of bottom-up model (World Energy Model (WEM))
IEA – Energy Technology Perspectives 2012 [9]	• 6°C Scenario • 4°C Scenario • 2°C Scenario	[81]	[81]	[81]	own compilation	use of bottom-up model (ETP-Times)
EIA – International Energy Outlook 2013 [74]	• Reference • High Eco. Growth • Low Eco. Growth • High Oil Price • Low Oil Price	[82], own calculations	[84], own calculations	own calculations (IEM Module)	(-)	use of bottom-up models (e.g. National Energy Modeling System, World Energy Projections plus (WEPS+))
ECF- Roadmap 2050 [75]	• Baseline • 4 different pathways	[83], Oxford Economics	[83]	[83]	[83], [85]	use of bottom-up approach
WEC -World Energy Scenarios [76]	• Jazz • Symphony	Own projections (based on debates with experts)	Own projections (based on debates with experts)	Own projections	Own projections	use of bottom-up model (Global Multi-Regional MARKAL)
E3m-Lab - Eu Energy, Transport and GHF Trends to 2050 [77]	• Reference 2013	?	[86]	own calculation (using the model PROMETHEUS)	(-)	use of bottom-up model (PRIMES) and sub-models
Greenpeace - Energy [r]evolution [78]	• Reference • Energy [R]evolution	[81]	[81]	own calculations based on [81] and with help of partners	[81], own compilation	use of bottom-up approaches
ExxonMobil - Outlook for Energy 2014 [79]		calculations based on internal data and on information from external sources including the International Energy Agency				no information provided
Shell – New Lens Scenarios [45]	• Mountains • Oceans	UN population division, EIA, Booz & company, Center for strategic and international studies (CSIS), the World Bank				no information provided

Table A.2: Cross-Impact data used for the demonstrator analysis.

	A			B			C		D			E			F		G			H		I			J		K		L			M	
	A1	A2	A3	B1	B2	B3	C1	C2	D1	D2	D3	E1	E2	E3	F1	F2	G1	G2	G3	H1	H2	I1	I2	I3	J1	J2	K1	K2	L1	L2	L3	M1	M2
A. Global development																																	
A1 convergence and prosperity				-2	1	-1	-1	1	-3	1	3	1	-1	0	0	0																	
A2 divergence				2	-1	-2	1	-1	-1	0	-1	-1	0	1	1	-1																	
A3 confrontation				-3	-1	3	1	-1	2	0	-2	-1	2	-1	1	-1																	
B. Oil price																																	
B1 stability									-1	1	2	0	0	0	0	0						0	0	0	0	0	0	0	0	0	0		
B2 medium growth									1	-1	-2	2	0	1	-1	1						-1	1	1	-1	1	-2	2	-1	1	1		
B3 rapid growth									2	1	-1	3	0	1	-2	2						-2	2	2	-2	2	-3	3	-2	2	2		
C. Population																																	
C1 slowly decreasing									0	0	0																						
C2 strongly decreasing									1	-1	-2																						
D. Economic growth																																	
D1 weak							-2	2				-1	0	1	3	-3						2	-1	-1	2	-2	1	-1	0	1	-1		
D2 medium							0	0				0	0	0	0	0						-1	1	0	1	-1	0	0	0	0	0		
D3 strong							3	-3				0	0	0	-1	1						-2	2	1	0	0	0	0	0	-1	1		
E. Political priority																																	
E1 energy turnaround									0	0	0				0	0	-2	1	1	-2	2	-1	0	1	-1	1	-1	1	-2	0	2		
E2 security									0	0	0				2	-2	-1	2	-1	-1	1	0	0	0	0	0	0	0	-2	2	0		
E3 economy									-1	1	1				1	-1	2	-1	-1	2	-2	2	0	-2	0	0	2	-2	0	0	0		
F. Acceptance energy turnaround																																	
F1 scepticism												-2	1	1						3	-3	2	1	-3	1	-1	0	0	2	-1	-1		
F2 approval												2	-1	-1						-3	3	-1	0	1	-1	1	-1	1	-2	1	1		
G. Planning legislation																																	
G1 incoherent															2	-2				3	-3	2	1	-3									
G2 promoting speed															3	-3				-3	3	-2	0	2									
G3 promoting participation															-3	3				-1	1	-1	0	1									
H. Infrastructure extension																																	
H1 slow															0	0						2	1	-3									
H2 fast															2	-2						-1	0	1									
I. Growth of renewable energies																																	
I1 slow															0	0				0	-3								3	0	-3		
I2 medium															2	-2				0	0								3	0	-3		
I3 fast															2	-2				-2	2								-1	-1	2		
J. Domestic energy savings																																	
J1 small																						0	0	0									
J2 strong																						1	0	-1									
K. Industrial energy savings																																	
K1 small																						0	0	0									
K2 strong																						1	0	-1									
L. Mobility																																	
L1 persistent structures																																	
L2 downscaling																																	
L3 downscaling and e-cars																																	
M. Climate change																																	
M1 strong												2	-1	-1	-1	1																	
M2 moderate												0	0	0	1	-1																	

Table A.3: 25 context scenarios identified by CIB analysis. For explanation see Table 2. Non-numerical scenario sequence, optimized for compacted representation.

<table>
<tr><th>S16</th><th>S18</th><th>S7</th><th>S6</th><th>S4</th><th>S24</th><th>S9</th><th>S3</th><th>S5</th><th>S10</th><th>S12</th><th>S11</th><th>S25</th><th>S17</th><th>S22</th><th>S21</th><th>S20</th><th>S15</th><th>S2</th><th>S1</th><th>S13</th><th>S14</th><th>S19</th><th>S23</th><th>S8</th></tr>
<tr><td>Scenario No. 16</td><td>Scenario No. 18</td><td>Scenario No. 7</td><td>Scenario No. 6</td><td>Scenario No. 4</td><td>Scenario No. 24</td><td>Scenario No. 9</td><td>Scenario No. 3</td><td>Scenario No. 5</td><td>Scenario No. 10</td><td>Scenario No. 12</td><td>Scenario No. 11</td><td>Scenario No. 25</td><td>Scenario No. 17</td><td>Scenario No. 22</td><td>Scenario No. 21</td><td>Scenario No. 20</td><td>Scenario No. 15</td><td>Scenario No. 2</td><td>Scenario No. 1</td><td>Scenario No. 13</td><td>Scenario No. 14</td><td>Scenario No. 19</td><td>Scenario No. 23</td><td>Scenario No. 8</td></tr>
<tr><td colspan="5">A. Global development: A1 convergence and prosperity</td><td colspan="2">A. Global development: A3 confrontation</td><td colspan="4">A. Global development: A1 convergence and prosperity</td><td>A. Global development: A2 divergence</td><td colspan="5">A. Global development: A1 convergence and prosperity</td><td colspan="4">A. Global development: A2 divergence</td><td colspan="2">A. Global development: A1 convergence and prosperity</td><td colspan="2">A. Global development: A3 confrontation</td></tr>
<tr><td colspan="5">B. Oil price: B2 medium growth</td><td colspan="2">B. Oil price: B3 rapid growth</td><td colspan="4">B. Oil price: B2 medium growth</td><td>B. Oil price: B1 stability</td><td colspan="5">B. Oil price: B2 medium growth</td><td colspan="4">B. Oil price: B1 stability</td><td colspan="2">B. Oil price: B2 medium growth</td><td colspan="2">B. Oil price: B3 rapid growth</td></tr>
<tr><td colspan="3">C. Population: C1 slowly decreasing</td><td colspan="7">C. Population: C2 strongly decreasing</td><td colspan="11">C. Population: C1 slowly decreasing</td><td colspan="4">C. Population: C2 strongly decreasing</td></tr>
<tr><td colspan="3">D. Economic growth: D3 strong</td><td colspan="2">D. Economic growth: D2 medium</td><td colspan="4">D. Economic growth: D1 weak</td><td>D. Economic growth: D2 medium</td><td colspan="9">D. Economic growth: D3 strong</td><td colspan="4">D. Economic growth: D2 medium</td><td colspan="2">D. Economic growth: D1 weak</td></tr>
<tr><td colspan="2">E. Political priority: E3 economy</td><td colspan="3">E. Political priority: E1 energy turnaround</td><td colspan="2">E. Political priority: E2 security</td><td colspan="6">E. Political priority: E1 energy turnaround</td><td colspan="10">E. Political priority: E3 economy</td><td colspan="2">E. Political priority: E2 security</td></tr>
<tr><td colspan="9">F. Acceptance energy turnaround: F1 scepticism</td><td colspan="4">F. Acceptance energy turnaround: F2 approval</td><td colspan="12">F. Acceptance energy turnaround: F1 scepticism</td></tr>
<tr><td colspan="2">G. Planning legislation: G1 incoherent</td><td colspan="6">G. Planning legislation: G2 promoting speed</td><td colspan="5">G. Planning legislation: G3 promoting participation</td><td colspan="10">G. Planning legislation: G1 incoherent</td><td colspan="2">G. Planning legislation: G2 promoting speed</td></tr>
<tr><td colspan="2">H. Infrastructure extension: H1 slow</td><td colspan="11">H. Infrastructure extension: H2 fast</td><td colspan="12">H. Infrastructure extension: H1 slow</td></tr>
<tr><td colspan="9">I. Growth of renewable energies: I2 medium</td><td colspan="4">I. Growth of renewable energies: I3 fast</td><td colspan="2">I. Growth of renewable energies: I1 slow</td><td>I. Growth of renewable energies: I2 medium</td><td colspan="9">I. Growth of renewable energies: I1 slow</td></tr>
<tr><td>J. Domestic energy savings: J1 small</td><td colspan="3">J. Domestic energy savings: J2 strong</td><td colspan="5">J. Domestic energy savings: J1 small</td><td colspan="6">J. Domestic energy savings: J2 strong</td><td colspan="10">J. Domestic energy savings: J1 small</td></tr>
<tr><td colspan="2">K. Industrial energy savings: K1 small</td><td colspan="11">K. Industrial energy savings: K2 strong</td><td>K. Industrial energy savings: K1 small</td><td colspan="3">K. Industrial energy savings: K2 strong</td><td colspan="5">K. Industrial energy savings: K1 small</td><td colspan="3">K. Industrial energy savings: K2 strong</td></tr>
<tr><td colspan="5">L. Mobility: L1 persistent structures</td><td colspan="2">L. Mobility: L2 downscaling</td><td colspan="2">L. Mobility: L1 persistent structures</td><td colspan="4">L. Mobility: L3 downscaling and e-cars</td><td colspan="10">L. Mobility: L1 persistent structures</td><td colspan="2">L. Mobility: L2 downscaling</td></tr>
<tr><td colspan="2">M. Climate change: M2 moderate</td><td colspan="3">M. Climate change: M1 strong</td><td>M. Climate change: M2 moderate</td><td colspan="6">M. Climate change: M1 strong</td><td colspan="6">M. Climate change: M2 moderate</td><td colspan="2">M. Climate change: M1 strong</td><td colspan="4">M. Climate change: M2 moderate</td><td>M. Climate change: M1 strong</td></tr>
</table>